

Review Article

Use of Nanofluids in Solar PV/Thermal Systems

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The continuous growth in the energy demand across the globe due to the booming population, in addition to the harmful effects of the fossil fuels on the environment, has made it essential to harness renewable energy via different technologies and convert it to electricity. The potential of solar energy still remains untapped although it has several advantages particularly that it is a clean source to generate both electricity and heat. Concentrating sunlight is an effective way to generate higher throughput per unit area of the absorber material used. The heat extraction mechanisms and the fluids used in solar thermal systems are key towards unlocking higher efficiencies of solar thermal systems. Nanofluids can play a crucial role in the development of these technologies. This review is aimed at presenting the recent studies dealing with cooling the photovoltaic thermal (PVT), concentrated photovoltaic thermal (CPVT), and other solar systems using nanofluids. In addition, the article considers the definition of nanofluids, nanoparticle types, nanofluid preparation methods, and thermophysical properties of the most common nanoparticles and base fluids. Moreover, the major factors which affect the nanofluid's thermal conductivity according to the literature will be reviewed.

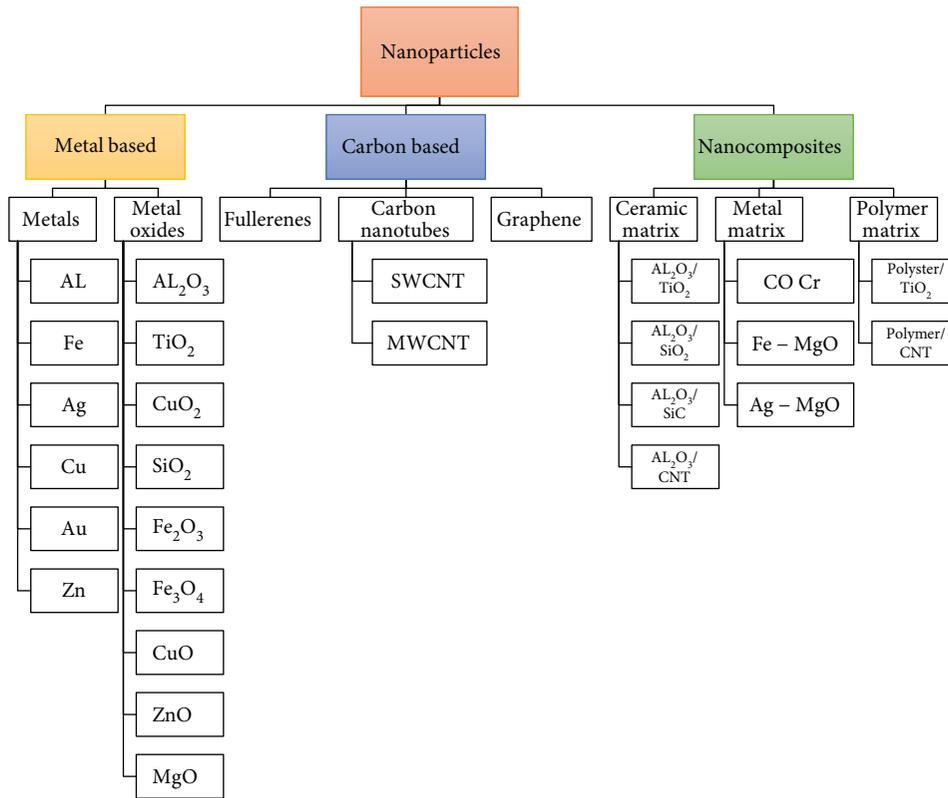
1. Introduction

Solar energy can play a vital role in saving our planet from the impacts of climate change caused by the use of fossil fuels to meet our energy demands. Therefore, enhancing the performance of solar energy technologies is of crucial importance. Solar PV is proving to compete side by side with fossil fuels today. A key challenge however is the increase in the temperature of the solar cells which affects their electrical efficiencies. Consequently, researchers have developed a new strategy to remove the excess heat from these systems to reduce their temperatures by using nanotechnology so the electrical efficiency can be raised [1, 2]. Nanotechnology is a multidisciplinary field which combines science, engineering, and technology together at a nanoscale [3]. There is a wide range of applications where nanotechnology can take place, for instance, material science, biology, and engineering. In the solar energy field, nanotechnology can positively participate by replacing the working medium with nanofluids. Nanofluid is a new type of heat transfer fluid which allows more heat to be removed from the solar system. The

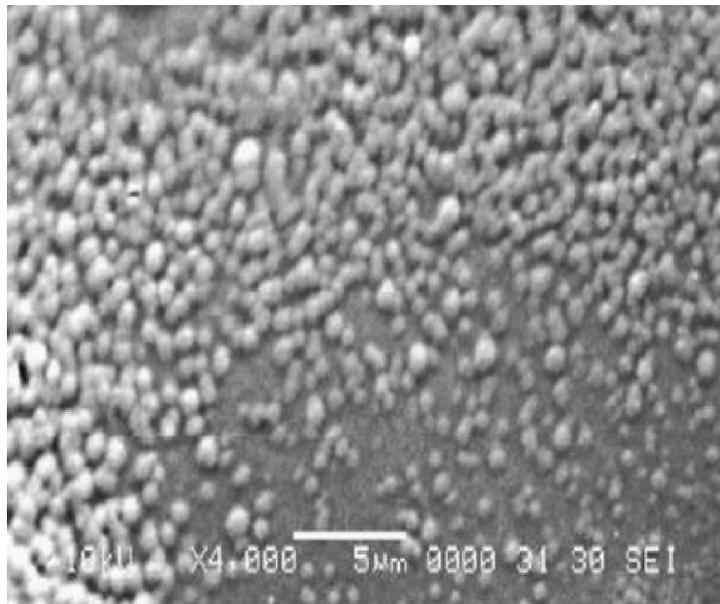
concept of using nanoparticles with the base fluids (see Section 1.1) is to increase the thermal conductivity which can cause a higher heat transfer coefficient as well as higher thermal efficiency.

1.1. Nanofluid Definition. Nanofluid has been defined in different ways in the literature but many researchers agree that it is a mixture of nanoparticles, which have a diameter ranging from 1 to 100 nm, dispersed efficiently in a base fluid [4–9]. These base fluids can be water, refrigerant, ethylene glycol, or thermal oils [6, 7, 10]. By using nanofluid, the heat transfer through the fluid can be enhanced as well as the thermal performance of the whole system [11].

1.2. Nanoparticle Classification. Nanoparticles can be classified as shown in Figure 1(a) [4, 7, 12] into metal based, carbon based, and nanocomposites. The metal-based nanoparticles can be further divided into two groups: metals (Al, Fe, Cu, etc.) and metal oxides which are a chemical compound of metal and oxygen (TiO₂, Cu₂O, ZnO, etc.). The carbon-based nanoparticles can be categorized into three



(a)



(b)

FIGURE 1: (a) Nanoparticle classification and types. (b) Scanning Electron Microscopy (SEM) image of agglomerated CuO nanoparticles.

types: fullerenes (a molecular form of carbon C_n , where $n > 20$) [13], carbon nanotubes which are carbon allotropes with cylindrical nanostructure, and graphene which is a carbon with two-dimensional allotropic form. The final group is nanocomposites, which are a particularly distinctive type of nanoparticles. This category consists of two dissimilar types of particles with diameters less than 100 nm [14]. These

nanocomposites may be classified into ceramic matrix, metal matrix, and polymer matrix.

These types of nanoparticles can boost the thermal properties of the base fluid as they have high thermal conductivity. This thermal conductivity can enhance the overall performance of the system which leads to a decrease in the operating cost [5, 15–17]. Moreover, nanofluids can work as optical

filters for the photovoltaic cells as they can catch all of the redundant solar energy that is not useful for PV working range as well as reducing the cells' temperature [5] [18].

Nanofluids have some advantages and drawbacks as follows:

(a) Advantages

- (i) Improving the heat transfer coefficient of the working fluid by raising its thermal conductivity [7, 19]
- (ii) Allowing the fluid to convey high amounts of thermal energy by raising the density and specific heat product [7]
- (iii) Boosting the heat transfer between the fluid and the receiver [7]
- (iv) Enhancing both the thermal and electrical efficiencies of the PV system
- (v) Lowering the absorber temperature therefore protecting the material

(b) Challenges

Although nanofluids enhance the heat transfer phenomena, there are several challenges to their implementation such as the following:

- (i) The high cost of production and preparation [19, 20]
- (ii) Using nanofluids may lead to high operating cost due to the increase in the pump work [7, 8, 21, 22]
- (iii) Sometimes when the operating conditions of the system are by natural convection and exposed to high temperature, the nanoparticles could agglomerate and show an unstable behavior [23]. Figure 1(b) shows the Scanning Electron Microscopy (SEM) image of CuO nanoparticles agglomerated during experiments which have a negative effect on the performance of the system [24]
- (iv) Nanoparticles can cause erosion and corrosion to the metallic components of the system or even clog the flow passages [20]. Celata et al. [25] stated that the erosion depends on the pipe's material. They undertook experiments on two tube types: stainless steel and copper. They noticed that by using stainless steel tube, there was no erosion when using water or nanofluids in contrast to copper tube where the erosion was uniformly distributed through the tube
- (v) Many authors state that nanoparticles may have some toxic effects on the environment and human health [26, 27]

1.3. Preparation of Nanofluids. In order to ensure significant performance, nanofluids need a successful preparation step to achieve stability of the suspended particles within the base

fluid as well as their uniformity [28]. There are two ways to prepare nanofluids.

- (a) *Single Step Method.* In this process, the dispersion and production of nanoparticles occur in the same step. This method can be carried out either by physical or chemical means [29]. In the physical method, the ultrasonic-aided submerged arc system is used for the synthesis of nanoparticles. The electrical energy generated from titanium electrodes which are merged in the dielectric liquid is used to melt the nanoparticles and vaporizes the deionized water. After this, in the vacuum chamber, the nanofluid, which is the mixture of the melted nanoparticles and deionized water, is formed [30, 31]. On the other hand, the chemical method depends on adding a reducing agent to the mixture of nanoparticles and base fluid followed by stirring and heating [31].
- (b) *Two-Step Method.* In this method, the nanoparticles are prepared as a first stage and then mixed with the base fluid by using high shear or ultrasound methods. Table 1 indicates the advantages and drawbacks of both the single and two-step methods. In order to ensure that the nanoparticles are stable inside the base fluid, different techniques have been used. Firstly, by using ultrasonication process, this approach is appropriate for nanofluid volumes from 0.2 to 2000 mL and produces a nanofluid with high stability and is considered the most popular method for preparation [31]. This process can be classified into either direct or indirect ultrasonication.

Direct sonication means that the mixture is in direct contact with the ultrasonic probe or horn. In this process, the required amount of both the nanoparticles and base fluid is weighed, then added into a vessel. The mixture should be stirred with a very thin metal rod for 1 minute followed by direct ultrasonication for 30 to 45 minutes. However, if the nanofluid is prepared by using the ultrasonic bath or pulsed ultrasonic, this process will be categorized as indirect sonication. In this case, the mixture of nanoparticles and host fluid is kept inside a vessel which is immersed into a bath. Through this bath, the ultrasonic pulsations are transferred. This method is not preferable for high viscous-based nanofluid [32].

Unlike the ultrasonication process, high-pressure homogenizer is considered the most effective method for nanofluid preparation. However, this technique suffers from some disadvantages: huge size and weight, high cost, and limited processing capacity at a time (5-50 mL) [33]. Another mixing procedure is known as mechanical stirrer (overhead stirrer) which can mix large volumes up to 20 L. However, it is not an effective way to avoid particle agglomeration if compared with other treatment methods [33]. In addition to the previous techniques, a shaker (disperse) is suitable for nanofluid preparation at ambient conditions. In addition, this is highly efficient for mixing nanoparticles with refrigerants to form the nanofluids. This mixture is

TABLE 1: Advantages and disadvantages of the single and two-step method [28, 29].

Property	Single step method	Two-step method
Stability	✓ (high level) [34]	✓ achieved by adding reactants and surfactants [35]
Avoiding agglomeration	✓ (low level)	✓
Avoiding storage and transportation	✓	
Simple	—	✓
Large quantity produced	—	✓
Particle uniformity	—	✓
Quick process	—	✓
Dispersion	✓ (totally)	✓ (partially)

called nanorefrigerant. Also, it can be useful for gaseous and low-temperature fluids.

2. Applications of Nanotechnology in PV/T Systems

To date, the effect of using only a limited number of nanoparticles on the performance of photovoltaic thermal systems has been studied. These types include silicon carbide (SiC) and metal oxides (SiO_2 , Al_2O_3 , TiO_2 , ZnO , Fe_3O_4 , and CuO). A small number of researchers have conducted research to study the effect of using carbon-based nanoparticles on the efficiency of the PVT. This section presents the studies carried out in this field using the aforementioned nanoparticles. Figure 2 summarizes the working idea of using a nanofluid to cool down a solar cell subjected to solar radiation. Using this type of cooling medium with PV systems allows the extraction of heat to be used in other thermal applications. Moreover, decreasing the PV cell's temperature leads to higher electricity generation.

A number of authors, such as Manikandan and Rajan [36], consider this technique in their research. They carried out an experimental study to evaluate the performance of sand-propyleneglycol-water nanofluid and its applicability in the solar energy field. The two-step method was used to prepare this nanofluid, and the stability (thermal conductivity) was measured over 6 months. The measurements showed that the thermal conductivity changed only by $0.002 \text{ W/m} \cdot \text{K}$ which represents merely a 0.5% change in its value. Further, the authors conducted a comparison between the sand-PG-water nanofluid and the PG-water in terms of the enhancement in the collection efficiency of solar energy. The experiments showed a higher temperature rate in the case of sand-PG-water (0.5 vol%) than in that of using only PG-water. In addition, for the volume fraction of 2 vol% of nanoparticles, the enhancement in the collection efficiency reached 16.5%.

Silicon carbide (SiC) has been an attractive type of nanoparticles for a number of researchers. Al-Waeli et al. [37] provided experimental research on enhancing the performance of the PVT system using nanofluid (SiC/water). The

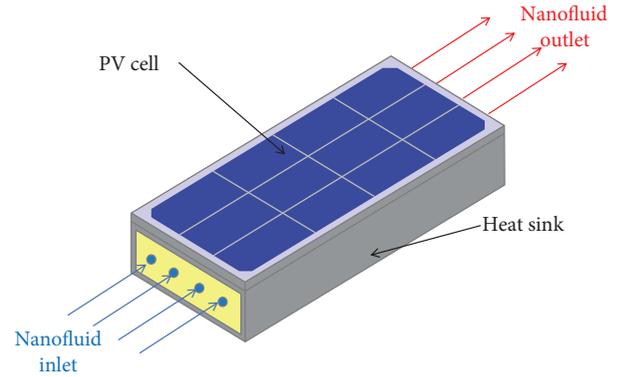


FIGURE 2: Schematic diagram of Photovoltaic Solar Thermal System (PV/T) with nanofluid as a cooling medium.

authors tested several concentrations of nanoparticles (1, 1.5, 2, 3, and 4 wt%). They prepared the nanofluid using an ultrasonic shaker bath which showed a significant stability of the nanofluid when examined over 6 months. The results revealed that the thermal conductivity of the working medium improved up to 8.2%. In addition, adding 3 wt% of SiC led to a promising enhancement in both the electrical and thermal efficiencies by 24.1 and 100.19%, respectively.

Another experimental study was conducted by Al-Waeli et al. [38] where they built a novel design of the PVT system, in which a tank connected to it was filled with phase change material mixed with nanoparticles (SiC), to store the heat rejected from the system. This tank was able to exchange the heat from the fluid pipe inside it. The same tube was passed at the back of the PVT system to extract the heat from it. The fluid passing through this tube was nanofluid (SiC-water) to benefit from its ability to extract more heat. Adding nanoparticles to the PCM enhanced the charging and discharging processes. The nanoparticle volume fraction tested 0%, 1%, 2%, 3%, and 4%. The results showed that the new system enhanced the electrical current from 3.69 to 4.04 A and the electrical efficiency increased from 8.07 to 13.32% when compared to the conventional system.

Metal oxide nanoparticles have shown significant results when used with different base fluids. Sardarabadi and Passandideh-Fard [39] presented a numerical and experimental study of a photovoltaic thermal system cooled by different types of nanoparticles and water as a base fluid flowing through copper tubes at the back of the PV. A schematic diagram of the system is shown in Figure 3. These nanoparticles were as follows: Al_2O_3 , TiO_2 , and ZnO . The experimental and numerical findings showed that TiO_2 /water and ZnO /water enhanced the electrical efficiency more than Al_2O_3 /water. Regarding the thermal efficiency, ZnO /water exhibited significant values if compared with the two other types. In addition, they studied the effect of increasing the mass fraction of ZnO from 0.05 to 10% by weight. While the thermal efficiency increased by four times, the temperature reduced by only 2% and the electrical efficiency by 0.02%.

Khanjari et al. [40] performed a CFD analysis of a PVT system using Ag-water and aluminum-water nanofluids. The results exhibited that the efficiency, as well as the heat

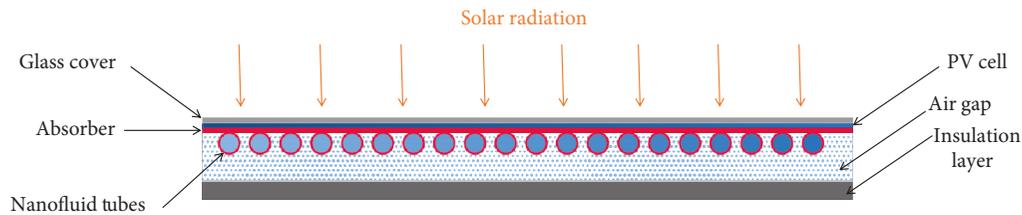


FIGURE 3: Schematic diagram of the PV/T system working on nanofluids.

transfer coefficient, increased by raising the nanoparticle volume of fraction. The heat transfer coefficient at $\phi = 5\%$ for alumina-water nanofluid increased by 2% with increasing the inlet velocity from 0.03 to 0.23 m/s. On the other hand, the heat transfer coefficient in the case of using Ag-water nanofluid was higher and varied from 28 to 45%. The thermal efficiency of using Al_2O_3 -water and Ag-water rose by 3 and 10%, respectively, when the volume fraction increased from 1 to 10%. In addition, the enhancement in the electrical efficiency of Ag-water was greater than Al_2O_3 -water.

Hashim et al. [41] conducted an experimental investigation of the effect of using Al_2O_3 -water as a cooling medium for the PVT system by applying forced convection. Different concentrations of Al_2O_3 -water were applied (0.1, 0.2, 0.3, 0.4, and 0.5%). The authors concluded that at a concentration of 0.3%, the temperature dropped significantly to 42.2°C and the electrical efficiency rose to 12.1%. On the other hand, increasing the concentration ratio higher than this value caused raising the temperature again to 52.2°C while the electrical efficiency declined to 11.3%.

Elmir et al. [42] presented a simulation study for a one-way channel at the back side of the PV/T system, the flow inside this channel being nanofluid Al_2O_3 /water ($\phi = 0\%$ to 10%). The solar cells were made from silicon, and the inclination angle was set at 30°. The authors used Brinkman and Wasp models to predict the physical properties. The results revealed that using nanofluid enhanced the heat transfer rate in the system and imposing low values of Reynolds number ($Re = 5$) boosted the heat transfer rate by 27% at $\phi = 10\%$.

Rejeb et al. [43] introduced the experimental and numerical studies of a PVT system cooled by several types of nanofluids. The authors tested different types of nanoparticles (Al_2O_3 and Cu) at several concentrations (0.1, 0.2, and 0.4 wt%) with different base fluids (water and ethylene glycol) on the electrical and thermal efficiencies of the system. The results confirmed that the performance (thermal and electrical efficiencies) of water as a base fluid is more effective than ethylene glycol. The numerical model was used to predict the annual electricity production for three different cities: Lyon (France), Mashhad (Iran), and Monastir (Tunisia). In addition, Cu/water showed higher electricity output for the three different cities reaching 791 kWh/m² in Monastir.

Nada et al. [44] presented an experimental study using Al_2O_3 nanoparticles ($d_{nm} = 20$ nm) with Rt_{55} paraffin wax for enhancing the efficiency of a photovoltaic system. The authors built three modules: the first one was the reference module, a PCM layer was integrated into the back side of the PV for the second configuration, and in the third one

PCM layer with nanoparticles was used. All of the modules were tested under Egyptian climatic conditions from 8 AM to 6 PM. A mechanical stirrer was used to mix the PCM with 2% of the nanoparticles. The findings showed that by using the PCM and nanoparticles, the efficiency improved by 13.2% and the temperature declined by 10.6°C while, in the case of using the PCM only, the efficiency boosted by 5.7% and the temperature decreased by 8.1% only.

Sardarabadi et al. [45] conducted an experimental study on the effect of using SiO_2 /water as a coolant in a PVT system. The mass fractions used were 1 and 3% by weight. The overall efficiency rose by 3.6 and about 7.9% for cases 1 and 3 wt%, respectively, if compared with using pure water only. In addition, the highest increase in both thermal and exergetic efficiency was observed at 3 wt% (12.8 and 24.31%, respectively).

Michael and Iniyar [46] carried out an experimental study by adding a thin copper sheet instead of a Tedlar layer to the silicon cell and used CuO/water as a cooling medium to enhance the performance of the system. The nanofluid was at 0.05% volume fraction. The authors tested the electrical and thermal efficiencies of the system with and without glazing. They found that the thermal efficiency when using glazing and nanofluid was enhanced by about 45% in comparison with water only, while the electrical efficiency reduced by roughly 3%. The authors attributed this reduction to the need for a new heat exchanger with higher effectiveness.

Ghadiri et al. [47] introduced an experimental study of cooling a PVT system by using a ferrofluid (Fe_3O_4 – water). The authors studied the effect of different mass concentrations (1 and 3 wt%) as well as changing the solar radiation (600 and 1100 W/m²) on the overall efficiency and exergy rate. In addition, the performance of the ferrofluid was investigated under constant and magnetic field. The findings confirmed that ferrofluid enhanced the overall efficiency by about 76% at 3 wt% if compared with using distilled water only. On the other hand, this value can be improved by 3% and the exergy rate by about 46% if the system is accompanied by an alternating magnetic field of 50 Hz.

A comparison between silicon carbide and metal oxide nanoparticles has been introduced by Al-Shamani et al. [48]. The scholars experimentally investigated the cooling performance of a PVT system by using three different types of nanoparticles: SiO_2 , TiO_2 , and SiC with distilled water as a base fluid. These nanofluids were prepared by the two-step method, where the nanofluids were prepared by dispersing the nanoparticles in the distilled water by using an ultrasonic device. The efficiency of the system and thermophysical

properties of the nanofluids were tested outdoor under the Malaysian tropical climate conditions. The thermophysical properties (ρ , ν , and K) were tested under various concentrations (0.5 to 2 wt%). The researchers observed that the viscosity of all the nanofluids declined by raising the temperature from 25 to 60°C the opposite of the thermal conductivity. In addition, SiC had the highest photovoltaic thermal efficiency (81.73%) and electrical efficiency (13.52%) of the three types.

A carbon-based nanoparticle has been used by Hjerrild et al. [18]. They introduced an experimental and numerical model of a spectrally tailorable optical filter, synthesized from nanofluids (Ag – SiO₂ with 0.026 WT% and CNT in water), placed between the light source and the solar cell. These two types of nanoparticles were selected because of their high absorptivity of light. Also, CNT can enhance the heating rate of the nanofluid which allows more heat extraction. The findings showed that the combined efficiency was boosted by 30% if compared to the conventional model where the electrical efficiency increased by about 6.6%.

From the above discussion, it is clear that almost all the authors have concentrated their research on limited types of nanoparticles such as SiC, AL₂O₃, and SiO₂. Nevertheless, carbon-based nanoparticles such as multiwalled carbon nanotubes (MWCNTs) and graphene oxide are yet to be investigated.

3. Applications of Nanotechnology in CPVT Systems

In contrast to photovoltaic solar cells, concentrated photovoltaic systems use concentrators or mirrors as shown in Figure 4 to focus the sun light on a small highly efficient solar cells. Thus, both electrical and thermal efficiencies could increase if nanotechnology is adopted in the system.

Very little research has been carried out into using nanofluid as a cooling medium on the CPVT systems. Also, most have concentrated on metal, metal oxide, and silicon carbide nanoparticles. The effect of using metal nanoparticles on the enhancement of the efficiency of the CPVT system was investigated by Hassani et al. [49] and Rahbar et al. [50].

Hassani et al. [49] carried out numerical studies on two concentrated PVT system designs. The first one (D-1) had two separate channels, one channel for the optical nanofluid and the other channel for the thermal nanofluid. The second design was a double pass channel (D-2). The optical nanofluid consisted of Ag ($d_{nm} = 10$ nm) nanoparticles dispersed in Therminol VP-1 which is suitable for high-temperature applications and has the ability to absorb the long wavelength, while Ag can absorb the short wavelength. The thermal nanofluid is from Ag and suspended in water. The authors concluded that the overall efficiency showed a sharp increase for GaAs and SI at a solar concentration of 160 and 100 when the volume fraction grew from 0.001% to 1.5%. In addition, the study recommended that using two different types of fluids in a separate channel design is more efficient than the other design.

Rahbar et al. [50] presented mathematical modeling of a system consisting of a parabolic trough concentrator with the concentrated photovoltaic system working on Ag/water to

run an Organic Rankine Cycle. The numerical solution of the 1-D model was done by using Engineering Equation Solver (EES). The nanofluid was used as cooling fluid for the CPVT as well as an optical filter to extract only the useful solar spectrum for the concentrated photovoltaic system. The authors concluded that adopting nanofluid as a working medium with the CPVT system had a great influence on the electrical, thermal, and overall efficiencies (1.8%, 3.3%, and 5.1%, respectively, at CR = 13.05 compared to CPVT). This effect appeared after raising the concentration ratio higher than 7.

Metal oxide nanoparticles have attracted the attention of many scientists due to their stability. Xu and Kleinstreuer [51] introduced a numerical study of the effect of (AL₂O₃/water) nanofluid on the cooling of a concentrated silicon solar cell and a multijunction solar cell by using Maxwell's model for thermal conductivity. The results showed that nanofluids are not the most effective cooling medium for the triple junction solar cells in contrast with the silicon one. In addition, the researchers stated that using diathermic oil instead of water will give better performance for other thermal applications. In general, they agreed that nanofluids increased both the electrical and thermal efficiencies of the system.

Xu and Kleinstreuer [52] proposed another study in which they presented another mathematical study (2-D modeling) on the effect of using AL₂O₃/water as a cooling medium for a photovoltaic channel exposed to highly concentrated solar intensity. The channel was subjected to heat conduction and turbulent nanofluid convection. The influence of changing nanoparticle volume fraction (0 to 4%), Reynolds number at the inlet (3000 to 70000), inlet nanofluid temperature (15 to 45°C), and different channel height (2 to 14 mm) on the performance of the system were studied. The study was conducted by using ANSYS-CFX 14 (control volume method). The results showed that the cell efficiency increased by raising both the Reynolds number and the volume fraction and reducing the inlet nanofluid temperature. In addition, the authors observed that the maximum efficiency obtained was 20% at a concentration ratio of 200, inlet Reynolds number at 30,000, and channel height of 10 mm.

Srivastava and Reddy [53] studied different configurations of a parabolic trough concentrator (PTC) with a concentrating photovoltaic system in the case of a compound parabolic collector integrated and without one. In addition, they discussed the effect of using a different number of cells as well as various types of fluids: AL₂O₃/water, Syltherm 800, Therminol VP-1, and Therminol VP-59. The study was carried out by using SIMPLE solver in Fluent 16.1. It was concluded that using the CPC had a negligible effect on the performance of the system, the cooling rate at a concentration of 6% being lower than at 0% and 1%. The authors attributed this to agglomeration. In addition, the maximum thermal output was achieved by using Syltherm 800 which was 2592.42 W, while the highest electrical output (692.2 W) was observed by using AL₂O₃/water at a concentration of 1%.

Lelea et al. [54] introduced a numerical study by using ANSYS-Fluent on cooling CPVT microchannel by using AL₂O₃/water at different nanoparticle diameters (28 nm

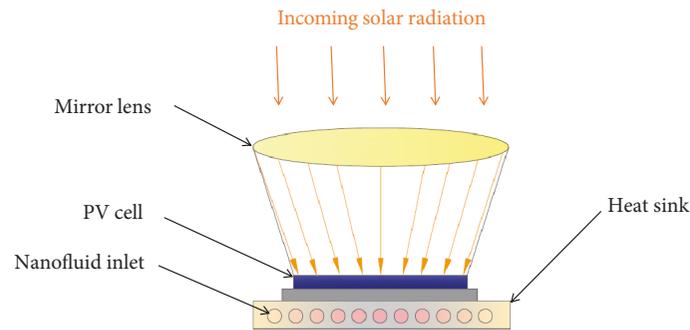


FIGURE 4: Schematic diagram of concentrated photovoltaic thermal systems.

and 47 nm) and concentrations (1%, 3%, and 5%). The single phase model was used to evaluate the kinematic viscosity and thermal conductivity. The authors claimed that the maximum temperature, in the case of using $\varnothing = 5\%$, was lower than in the case of water only.

Zarma et al. [55] built a mathematical 2-D model using ANSYS 19.0 to examine the performance of CPVT using PCM (calcium chloride hexahydrate) with different types of nanoparticles: Al_2O_3 , CuO, and SiO_2 . The nanoparticles were examined at different concentrations, 1 wt% and 5 wt%. The mixture of PCM and nanoparticles was in a rectangular container at the back surface of the solar cell with dimensions of height = 125 mm and length = 100 mm. The results of the numerical study revealed that the maximum performance achieved was by using Al_2O_3 at a concentration of 5 wt%, where the electrical efficiency was 8% and the temperature uniformity was $12^\circ C$. In addition, the authors stated that using nanoparticles with PCM improved the heat transfer rate by increasing the thermal conductivity of the mixture.

Yazdanifard et al. [56] presented a mathematical study of using TiO_2 /water as a working medium for a parabolic trough concentrator integrated with the concentrated photovoltaic receiver. The mathematical equations were solved by using the MATLAB software. The effect of increasing the volume fraction and flow regime was introduced. The results revealed that, in the case of laminar flow, when the volume fraction of the nanoparticles increases, both the kinematic viscosity and the thermal conductivity of the nanofluid rises. Therefore, at a constant mass flow rate, the Reynolds number decreased, which caused the heat transfer coefficient to develop. Hence, the photovoltaic temperature declined, the opposite of the case of turbulent flow. As a result of all of the above, there were greater increases in the thermal, electrical, and total efficiencies in the case of laminar more than in turbulent flow.

Menbari et al. [57] experimentally and numerically studied the effect of using CuO/water as a nanofluid on the performance of a direct absorption parabolic trough collector (DAPTC). The numerical and experimental results showed that the thermal efficiency of the system improved by increasing the nanoparticle volume of fraction from 0.002 to 0.008% as it rose from 18 to 52%. In addition, the authors stated that it enhanced the performance by increasing the flow rate from 20 to 100 L/hr.

Bellos and Tzivanidis [58] conducted mathematical research by using Solidworks flow simulation to perform optical, thermal, and flow studies about the effect of using Syltherm 800/copper oxide on the performance of the CPVT with parabolic trough concentrator; cross section of the studied receiver is shown in Figure 5. The absorber was made from PV silicon cell of a width of 100 mm, while the receiver aperture area was 0.1 mm^2 . The authors studied the effect of changing the inlet temperature (25 to $200^\circ C$) and the nanofluid flow rate (300 to 720 L/hr) on the flow properties (density, dynamic viscosity, and specific heat). The study concluded that using nanofluid improved the electrical, thermal, and total efficiency. In addition, there was a slight enhancement in the thermal efficiency after 540 L/hr. The maximum thermal, electrical, and total efficiencies at an inlet temperature of $100^\circ C$ and flow rate of 540 L/hr were 46.84, 6.60%, and 2.08%, respectively, which were greater than the values achieved by using pure oil only.

An et al. [59] presented an experimental study using Cu_9S_5 nanofluid as an optical filter in concentrating PVT as shown in Figure 6. This Oleylamine solution consists of Cu_9S_5 nanoparticles dispersed in Oleylamine ($C_{18}H_{37}N$). The particle diameter ranged from 50.5 to 73.7 nm, and the average diameter was 60.2 nm. In addition, three different concentrations of the nanofluid were used (22 ± 1.1 , 44.6 ± 2.2 , and 89.2 ± 4.5 ppm). The results revealed that increasing the particle concentration had a great influence on the performance of the system. Moreover, the maximum efficiency achieved by using this nanofluid at a high concentration was 34.2% which was higher than that of without optical filter (17.9%).

Comparison between metal oxide nanoparticle (Al_2O_3) and silicon carbide (SiC) was carried out by Radwan et al. [60] where they mathematically studied the effect of using both types of nanoparticles with water on the cooling of a low concentrated photovoltaic (LCPV) system. Mathematical modeling (2-D) was carried out by using ANSYS Fluent 16.2. The diameter of both Al_2O_3 and SiC was 20 nm, the volume concentration varied from 1% to 4%, and the Reynolds number was from 10 to 100. The authors stated that the performance of the low concentrated photovoltaic system was greater by using SiC/water than in the case of Al_2O_3 /water. In addition, a significant decrease in the cell temperature was observed by increasing the volume fraction of both types of nanofluids. The same results were obtained at large

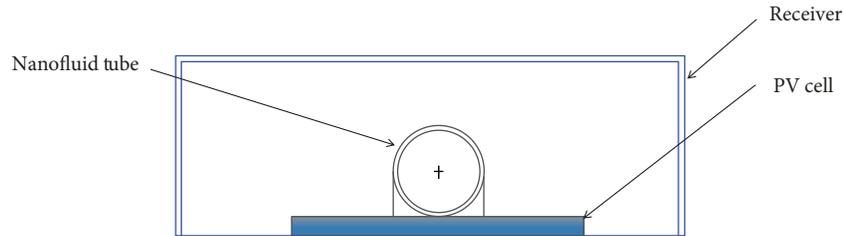


FIGURE 5: Cross section of the studied receiver.

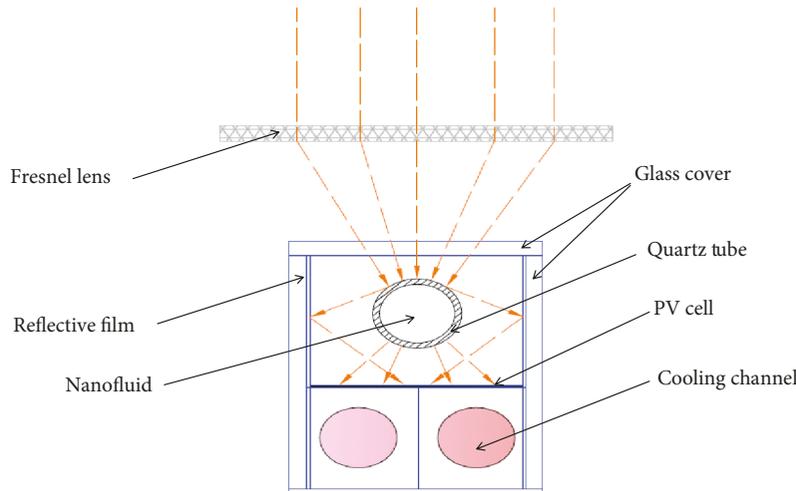


FIGURE 6: The experimental set up of concentrated photovoltaic thermal.

values of the concentration ratio and low values of Reynolds number for both nanofluids. There was a significant improvement in the thermal efficiency by using nanofluids at concentration ratios lower than 17.8. After this value, the thermal efficiency declined by using nanofluids. Large values of net electrical power and output thermal power were observed at $Re = 10$ and $CR = 10$ when the nanoparticles volume of fraction increased.

This research was followed by 3-D modeling using ANSYS 17.2 to study the effect of using Al_2O_3 and SiC (nanoparticle diameter = 20 nm) with water as a base fluid on the performance of a microchannel heat sink within a concentrated photovoltaic system [61]. The parameters studied were nanoparticle volume of fractions, flow Reynolds number, systems' power, and efficiencies. Compared to Al_2O_3 /water, SiC/water showed better performance in terms of cell temperature uniformity, net electrical power of the solar cell, and electrical efficiency. In addition, the authors agreed that 4% of SiC caused a decrease in the maximum local solar cell temperature (from $8^\circ C$ to $13^\circ C$) compared with pure water.

From the above review, there is no doubt that utilizing nanofluids as a cooling medium for the CPVT has a noteworthy effect on the performance. The researchers focused their work on mathematical modeling with a small number who conducted experimental research. In addition, there has been a major focus on metal oxide nanoparticles although carbon-based nanoparticles have higher thermal conductivity and could absorb more heat from the system.

4. Other Studies Dealt with Nanoparticles as a Working Medium

Due to the benefits of nanofluids over conventional options, various scientists have conducted several studies to examine the performance of the direct absorption solar collector (DASC), flat-plate and U-tube solar collectors (FP&UTC), and evacuated tube solar collector (ETSC).

Otanicar et al. [62] presented experimental and numerical studies on the effect of using different nanoparticles (graphite sphere-based, carbon nanotube-based, and silver sphere-based), as a cooling medium, on a direct absorption solar collector (DASC). These nanoparticles were tested with water at a range of volume of fractions and particle sizes. The authors concluded that graphite nanoparticles can increase the collector efficiency by only 3% if compared with the conventional flat surface absorber if the volume of fraction is equal to 5%. On the other hand, by using silver nanoparticles, the efficiency enhanced by 5%, while by using CNT, a small difference can appear. After a volume of fraction of 5%, the efficiency began to decrease slightly.

Kang et al. [63] experimentally evaluated the performance of both the flat-plate and U-tube solar collectors if the nanofluid is used (Al_2O_3 -water) under several volume concentrations (0.5, 1, and 1.5%) and nanoparticle sizes (20, 50, and 100 nm). Regarding the flat-plate solar collector, the efficiency increased to 72.4% when using the nanofluid instead of water at a volume fraction of 1% and nanoparticle size of 20 nm. This value was the maximum if compared with

those at nanoparticle size 50 and 100 nm. In addition, the efficiency of the flat-plate solar collector increased by 3.5% if compared with the U-tube solar collector after using (Al_2O_3 -water). Therefore, the solar collector's performance was enhanced when the particle size decreased. Further, the authors concluded that the maximum efficiencies for both the flat-plate and U-tube solar collectors occurred at 1% volume of fraction.

Yousefi et al. [64] experimentally studied the effect of using MWCNT/water as a nanofluid for absorbing heat from the flat-plate solar collector (FPSC). The effect of several parameters was studied on the performance of the flat-plate solar collector; MWCNT weight of fraction (0.2% and 0.4%), using surfactant of Triton, nanofluid mass flow rate ranged from 0.0167 to 0.05 kg/s. The Triton X-100 was added to the nanofluid in the ratio of 1:350 in order to achieve the maximum dispersion. Also, the two-step method was applied using the 400S Ultrasonic model for 30 minutes, and the mixture was stable for up to 10 days. In comparison with water, the nanofluid enhanced the heat transfer in the flat-plate solar collector and boosted the thermal efficiency by using the chemical surfactant. Moreover, the maximum thermal efficiency was achieved at 0.05 kg/s and fraction weight of 0.4%.

Kiliç et al. [65] introduced an experimental study on the impact of using TiO_2 ($d_{\text{nm}} = 44\text{nm}$)/water with a concentration of 2 wt% on the effectiveness of the flat-plate solar collector. The authors used the two-step method to prepare the nanofluid, using surfactant—Triton X-100—at a concentration of 0.2 wt% to keep the prepared nanofluid stable and avoid agglomeration. After that, they exposed the mixture to ultrasonic bath. The maximum achieved instantaneous efficiency of the collector by using this nanofluid was 48.672% whereas it was only 36.204% by using water only.

Verma et al. [66] investigated the influence of using two different hybrid fluids: (80%MgO + 20%MWCNTs)/water and (80%CuO + 20%MWCNTs)/water on the performance of a flat-plate solar collector. The diameters of CuO and MWCNT nanoparticles were 42 nm and 7 nm MWCNT, respectively. The concentration of the samples was 0.25, 0.5, 0.75, 1, 1.25, 1.5, and 2 vol%. Both of the hybrid fluids were prepared by using the two-step method. Initially, the mixture of CuO/water and MgO/water at maximum concentration was prepared by using deionized water. After that, MWCNT was added in the solution, followed by ultrasonic agitation, and then ultrasonic bath for 2 hr. The authors stated that both the energetic and exergetic efficiencies of MgO (71.54% and 70.55%, respectively) hybrid nanofluid were much greater than that in the case of CuO hybrid fluid (70.63% and 69.11%, respectively).

Chougule et al. [67] introduced experimental research on using carbon nanotubes (CNT)/water at a concentration of 0.15 vol%, diameter of 10–12 nm, and length of 0.1–10 μm . The idea of the research was examining this type of nanofluid inside copper heat pipe as a cooling method for flat-plate collectors. The authors studied the performance of the system under several conditions: changing the collector angle with a fixed position and activating the tracking mechanism of

the collector. They found that the best performance (45%) was at a tilt angle of 31.5°.

Ghaderian and Sidik [68] performed experimental research to examine the effect of using Al_2O_3 /distilled water on the performance of the evacuated tube solar collector (ETSC). The volume fractions used were 0.03 and 0.06% (particle diameter of 40 nm), and the volume flow rate range of the nanofluid studied was from 20 to 60 L/hr. The authors prepared the nanofluid by using the two-step method which showed good stability over the following 7 days. The maximum average efficiency was achieved by using Al_2O_3 /distilled water as a working medium that was 58.65% at 0.06% volume fraction and flow rate of 60 L/hr, which was considered a very high value if compared with using water only (22.85%).

Iranmanesh et al. [69] carried out experimental research on using graphene nanoplatelets GNP/distilled water as a working fluid inside the evacuated tube solar collector. The mass fractions tested were 0.025, 0.05, 0.075, and 0.1 wt% at a volume flow rate of 0.5, 0.1, and 1.5 L/min. The authors prepared the nanofluid by using ultrasonication probe without any surfactants which showed good stability for the following three months after the initial preparation. The experiments revealed that the maximum efficiency of the collector occurred at nanoparticle concentration of 0.1 wt% and a volume flow rate of 1.5 L/min. This value was 90.7% which was greater than that of using distilled water only (54.81%).

Liu et al. [70] experimentally investigated the efficiency of the evacuated tube solar collector which was integrated with a compound parabolic concentrator (CPC) by using CuO/water with a concentration of 1.2 wt% and a diameter of 50 nm. The nanofluid was prepared by using the two-step method, by suspending the nanofluid on the water followed by oscillating it in an ultrasonic bath. The performance of the system was enhanced by using nanofluid by 12.4% at an air outlet temperature 160°, whereas the maximum efficiency achieved was 57.6% at an air outlet temperature of merely 130°.

Mahendran et al. [71] experimentally examined the influence of using TiO_2 /water on the performance of the evacuated tube solar collector. The outdoor tests took place in Malaysia where the daily solar isolation reached 900 W/m². The nanoparticle diameter was 30 to 50 nm and the volume of fraction concentration was 0.3%. Preparation of the nanofluid was conducted by using the two-step method; the authors used the mechanical stirrer for 2 hours in order to ensure that the mixture was homogenous. The maximum efficiency achieved by using nanofluid was 73% which was higher than the case of using water only by 16.67% where the volume flow rate was 2.7 L/min.

Hussain et al. [72] undertook an experimental study on the effect of using two different types of nanofluids Ag ($d_{\text{nm}} = 30\text{nm}$)/water and ZrO_2 ($d_{\text{nm}} = 50\text{nm}$)/water on the evacuated tube solar collector efficiency. The nanoparticles were at different concentrations: 0, 1, 3, and 5 vol% and different mass flow rates of 30, 60, and 90 liter/hr · m². The two-step method was used for preparing the nanofluid; after dispersing the nanoparticles in distilled water, ultrasonic

mixing was applied using surfactant, but the mixture remained stable for 4 hours. The authors claimed that the efficiency of the solar collector achieved by using Ag/water was 21.05% at 5 vol% and 90 liter/hr · m² which was considered higher than in the case of using ZrO₂/water. Therefore, the Ag/water achieved better performance than ZrO₂/water.

Kaya et al. [73] examined experimentally the performance of an evacuated U-tube solar collector working with ZnO ($d_{nm} = 30$ nm)/ethylene glycol and pure water. The base fluids used were 50%ethylene glycol and 50%pure water; the nanofluid tested was at a volume concentration of 1%, 2%, 3%, and 4%; and three different mass flow rates (0.02, 0.03, and 0.045 kg/s). A surfactant agent polyvinylpyrrolidone (PVP) was added to the mixture of the base fluid (EG + water). Thereafter, the magnetic stirring was enabled to ensure that the nanofluid was homogeneous. The authors noted that the maximum efficiency (62.87%) of the solar collector was achieved at a volume concentration of 3% and a mass flow rate of 0.045 kg/s.

Tong et al. [74] studied the influence of using multiwalled carbon nanotube (MWCNT) nanoparticles with water on the performance of an enclosed type evacuated tube solar collector. The nanofluid was prepared by using the two-step method (gum arabic with 0.25 wt% concentration as a surfactant, followed by probe sonication). The efficiency of the system was tested under concentration volume of 0.06 to 0.24 vol% and mass flow rate of 0.01 kg/s. The theoretical and experimental results revealed that the heat transfer coefficient was enhanced by 8% by using nanofluid at 0.24 vol%.

Ozsoy and Corumlu [75] experimentally determined the efficiency of a thermosyphon heat pipe evacuated tube solar collector by using Ag/water as a working medium in the heat pipe. The nanofluid used was at a concentration of 20 ppm and prepared by using the two-step method. Firstly, the electrolysis method was applied to the mixture of silver and pure water. Secondly, the authors used tannic acid as a surfactant. The volumetric flow rate of the nanofluid was 0.18 L/min. The results revealed that the solar collector efficiency rose between 20.7% and 40%.

A conclusion for all the above studies has been summarized in Table 2.

5. Thermophysical Properties of the Most Common Nanoparticles and Base Fluids

This section introduces the thermophysical properties of both nanoparticles and base fluids that have been used in the literature. These thermophysical properties include density, specific heat, and thermal conductivity (Table 3).

6. Parameters That Have a Strong Effect on the Thermal Conductivity of the Nanofluid

As stated earlier, the idea behind using nanoparticle within the base (host) fluid is to increase the thermal conductivity of the carrying fluid which leads to boosting the heat transfer phenomenon through the system. Therefore, in this section, we discuss some important parameters that have a significant

influence on the thermal conductivity of the nanofluid as mentioned in the published studies.

6.1. Nanoparticle Volume Concentration. Nanoparticle volume concentration has a significant influence on the enhancement of the thermal conductivity of the nanofluid. Several studies have proven that increasing the volume fraction up to 5% [29] can increase the thermal conductivity, for example, as reported by Iranmanesh et al. [69] and Verma et al. [66].

6.2. Temperature. Increasing the temperature has a considerable effect on boosting the thermal conductivity of the nanofluid which has been revealed by Lee et al. [86], Al-Waeli et al. [37], Verma et al. [66], and Iranmanesh et al. [69] as the opposite of the behavior shown for viscosity. Nevertheless, Bellos and Tzivanidis [58] in their recent research confirmed that the thermal conductivity of the nanofluid decreased by increasing the temperature.

6.3. Particle Size. Nanofluid consists of base fluid and nanoparticles which have a diameter less than 100 nm. Therefore, it is preferred to use nanoparticles with small sizes to achieve a better enhancement in the thermal conductivity as well as in heat transfer. Kang et al. [63] discussed the effect of increasing the nanoparticles' diameter on the efficiency of the flat-plate solar collector. The results revealed that using a particle size of $d_{nm} = 20$ nm boosted the efficiency compared with $d_{nm} = 50$ nm and 100 nm.

6.4. Base Fluid Type. There are several types of base fluids, as stated above. Xie et al. [87] observed that using base fluid with low thermal conductivity is more efficient than using fluids with high thermal conductivity. In contrast, Rejeb et al. [43] argued that using water (as a base fluid) which has higher thermal conductivity than ethylene glycol led to great enhancement in the thermal conductivity for the same nanoparticle and operating conditions.

6.5. Nanoparticle Shape. Many researchers have studied the effect of the nanoparticle shape on fluid performance and its thermal conductivity [88]. Murshed et al. [89] studied two geometrical configurations of TiO₂ nanoparticle: cylindrical shape ($d = 10$ nm, $L = 40$ nm) and spherical shape ($d = 15$ nm). The experimental results showed that the cylindrical shape achieved greater improvement in thermal conductivity. Figure 7 shows a comparison of thermal conductivity improvement when using differently shaped nanoparticles; these include blades, platelets, cylinders, bricks, and spheres. It was found that the best thermal conductivity is achieved when using blades. The scientists attributed this to the large heat transfer area of the particles which conducts the heat through the fluid.

6.6. Effects of Adding Surfactants. The function of adding a surfactant or an additive is to prevent the agglomeration and sedimentation of the nanofluid and improve its stability. For example, these surfactants or additives can be sodium hexametaphosphate [57], sodium dodecyl-sulfate [62], Triton X-100 [65], or sodium dodecylbenzene sulphonate [46].

TABLE 2: Conclusion of the previous studies.

Application	Reference	Nanoparticles	Base fluid/medium	Concentration	d_{nm} (nm)	Thermal conductivity (W/(m·K))	Preparation method	Stability	Concentration	Thermal conductivity	Parameter studied			
											Viscosity	η_{hh} or $T_{f, out}$	$\eta_{f, lect}$	$\eta_{overall}$
PV/T	[37]	SiC	Water	1, 1.5, 2, 3, and 4 wt%	45 – 65 nm	370 – 490	Two step method (ultrasonic shaker)	Up to 6 months	✓	✓	✓	✓	✓	
	[38]	SiC	Water	0%, 1%, 2%, 3%, and 4% by volume.	45 – 65 nm	370 – 490	Two step method (ultrasonic shaker)	Up to 6 months	✓	✓	✓	✓	✓	
	[39]	Al ₂ O ₃	Water	0.2 wt%	20 nm	40	Two step method (ultrasonic vibrator)	Up to two days	✓	–	–	✓	–	
	[18]	TiO ₂	Water	0.026 wt%	10 – 30 nm	8.9	Two step method (ultrasonic bath followed by probe)	–	✓	–	–	✓	✓	
	[45]	ZnO	Water	0.026 wt%	10 – 25 nm	13	Two step method (ultrasonic processor)	Up to ten days	✓	–	–	✓	✓	
	[40]	Ag – SiO ₂	Water	1 and 3 wt%	6 – 13 nm	–	Numerical study (CFD)	–	✓	–	–	✓	✓	
	[41]	CNT	Water	1% to 12% by volume.	11-14 nm	–	–	–	–	–	–	–	–	–
	[47]	Ag	Water	0.1% to 0.5% (step 0.1%) by volume.	50 nm	–	–	–	–	–	–	–	–	–
	[43]	Al ₂ O ₃	Water	1 and 3 wt%	30 nm	–	–	–	–	–	–	–	–	–
	[46]	Fe ₃ O ₄	Water	0.1, 0.2, and 0.4 wt%	45 nm	40	Two step method (ultrasonic mixing)	At least one month	✓	–	–	✓	✓	–
CPV/T	[48]	Al ₂ O ₃	Water/ethylene glycol	0.05% by volume	75 nm	0.722 (nanofluid)	Two step method (ultrasonic processor)	From one (Triton X-100) to 3 days (SDBS surfactant)	–	✓	✓	✓	✓	
	[76]	CuO	Water	0.5, 1, and 2 wt%	–	–	Two step method (ultrasonic device)	–	✓	–	–	✓	✓	
	[42]	SiO ₂	Water	0.02 wt%	–	–	–	–	–	–	–	–	–	
	[60]	TiO ₂	Water	0% to 10% by volume	–	–	Numerical study	–	✓	–	–	–	–	
	[61]	Al ₂ O ₃	Water	Up to 4% by volume	20 nm	–	Numerical study (CFD)	–	✓	–	–	✓	–	
	[51]	SiC	Water	Up to 4% by volume	20 nm	40	Numerical study (CFD)	–	✓	–	–	✓	Net power	
	[49]	Al ₂ O ₃	Water	5% by volume	38.4 nm	150	Numerical study (CFD)	–	–	–	–	–	–	
	[55]	Ag	Therminol VP-1	0.001% to 1.5% by volume	10 nm	–	Numerical study	–	–	–	–	–	–	
	[55]	Al ₂ O ₃	PCM	1% and 5 wt%	59, 29, and 30 nm	40	Numerical study (CFD)	–	–	–	–	–	–	

The enhancement in the average and local Nusselt number @ different Re

TABLE 2: Continued.

Application	Reference	Nanoparticles	Base fluid/medium	Concentration	d_{nm} (nm)	Thermal conductivity (W/(m·K))	Preparation method	Stability	Concentration	Thermal conductivity	Parameter studied	η_{hh} or $T_{f,out}$	η_{elect}	$\eta_{overall}$
		CuO				18								
		SiO ₂				1.2								
	[59]	Cu ₃ S ₅	Oleylamine (C ₁₈ H ₃₇ N)	(0.00 to 89.2 ± 4.5) ppm	60.2 nm	0.170-0.176 (nanofluid)	Ultrasonic washer (before each test)	—	✓	✓	✓	✓	✓	✓
	[54]	Al ₂ O ₃	Water	1, 3, and 5% by volume	13, 28, 36, and 47 nm	—	Numerical study	—	✓	—	—	—	—	—
	[52]	Al ₂ O ₃	Water	Up to 4% by volume	38.4 nm	—	Numerical study (CFD)	—	✓	—	—	Cell temp.	Net power	—
	[58]	CuO	Syltherm 800 (thermal oil)	5% by volume	—	—	Numerical study (CFD)	—	✓	✓	✓	✓	✓	✓
CPV/T with PTC	[53]	Al ₂ O ₃	Water	0, 1, 6% by volume	—	—	Numerical study (CFD)	—	✓	—	—	✓	✓	✓
	[50]	Ag	Water	6% to 13% by volume	—	—	Numerical study (CFD)	—	✓	—	—	✓	✓	✓
	[56]	TiO ₂	Water	Up to 4% by volume	21 nm	—	Numerical study	—	✓	✓	✓	✓	✓	✓
DAPTC	[57]	CuO	Water	0.002% to 0.008% by volume	<100 nm	—	Two step method (ultrasonic probe with sodium hexametaphosphate surfactant)	Stable through the exp.	✓	—	—	✓	—	—
DASC	[62]	Graphite												
		Ag	Water	0% to 1% by volume	30 nm	—	Two step method (sonication with sodium dodecyl-sulfate surfactant)	—	✓	—	—	✓	—	—
		CNT												
	[63]	Al ₂ O ₃	Water	0.5%, 1%, and 1.5% by volume	20, 50, and 100 nm	—	—	Up to one week	✓	—	—	✓	✓	Cost analysis
	[64]	MWCNT	Water	0.2% and 0.4 wt%	10-30 nm	—	Two step method (ultrasonic probe) and (adding Triton X-100)	Up to 10 days	✓	—	—	✓	—	—
FP&UTSC	[65]	TiO ₂	Water	0.2 wt%	44 nm	—	Two step method (ultrasonic processor Bandelin Sonorex Super RK514H) with Triton-X 100	—	—	—	—	✓	—	—
	[66]	80%MgO + 20%MWCNTs	Water	0.25% to 2% by volume	42 nm (CuO), 7 nm (MWCNT)	—	Two step method (ultrasonic bath)	—	✓	✓	✓	✓	✓	—
	[67]	CNT	Water	0.15% by volume	10-12 nm, length of 0.1-10 μm	3.47 (nanofluid)	Chemicals followed by ultrasonic bath (two step method)	15 hr.	—	—	—	✓	—	—

TABLE 2: Continued.

Application	Reference	Nanoparticles	Base fluid/medium	Concentration	d_{nm} (nm)	Thermal conductivity (W/(m·K))	Preparation method	Stability	Concentration	Thermal conductivity	Parameter studied	η_{det}	$\eta_{overall}$
	[68]	Al ₂ O ₃	Water	0.03% and 0.06% by volume	40 nm	36	Two step method (adding Triton-X 100 followed by ultrasonic probe)	Up to one week	✓	✓	✓	—	—
	[69]	GNP	Water	0.025, 0.05, 0.075, and 0.1 wt%	5-10 nm	—	Two step method (ultrasonic probe) without surfactants	Up to three months	✓	✓	✓	—	—
	[70]	CuO	Water	1.2 wt%	50 nm	—	Two step method (ultrasonic bath)	—	—	—	✓	—	—
	[71]	TiO ₂	Water	0.3% by volume	30-50 nm	8.4	Two step method (followed by mechanical stirrer)	—	—	—	✓	—	—
ETSC	[72]	Ag ZrO ₂	Water	1%, 3%, and 5% by volume	30 nm 50 nm	429 22.7	Two step method (followed by ultrasonic mixing)	Up to 4 hrs	✓	—	—	—	—
	[73]	ZnO	50%ethylene glycol + 50%water	1% to 4% by volume	30 nm	27.2	Two step method (followed by magnetic stirrer)	—	✓	—	—	—	—
	[74]	MWCNT	Water	0.06 to 0.24% by volume	—	3000	Two step method (ultrasonic probe) followed by adding gum Arabic for stability	—	✓	✓	✓	Cost and environmental analyses	—
	[75]	Ag	Water	20 ppm	60 nm	—	Two-step method (followed by adding tannic acid as a reducing agent)	One year under observation	✓	—	—	—	—

TABLE 3: Nanoparticle and base fluid properties as stated in the literature.

Nanoparticle/base fluid type	Density, ρ_{np} (kg/m^3)	Specific heat, $c_{p,np}$ ($\text{J}/\text{kg} \cdot \text{K}$)	Thermal conductivity, K_{np} ($\text{W}/\text{m} \cdot \text{K}$)	Reference
Alumina (Al_2O_3)	3960	773	40	[77, 78]
Aluminum (Al)	2700	904	237	[78]
Carbon nanotube (CNT)	1350	—	3000	[78]
Copper (Cu)	8940	385	401	[78]
Copper oxide (CuO)	6000	551	33	[78]
Graphite	2160	701	120	[78]
Silicon (Si)	2320	714	148	[78]
Silicon carbide (SiC)	3370	1340	150	[78]
Silicon oxide (SiO_2)	3970	765	3970	[79]
Titanium carbide (TiC)	4930	711	330	[78]
Titanium oxide (TiO_2)	4230	692	8.4	[78]
Cuprous oxide (Cu_2O)	6320	42.36 J/mole · K	76.5	[79]
Graphene oxide (GO)	1910	710	1000	[79]
Iron oxide (Fe_2O_3)	5250	650	20	[80]
Single-walled carbon nanotubes (SWCNTs)	2100	841	6000	[81]
Multiwalled carbon nanotubes (MWCNTs)	2100	711	1500	[82]
(Ag) + (MgO) nanocomposite	7035	554.5	242	[83]
(Fe_3O_4) + (MWCNTs) nanocomposite	4845.4	680.66	509.14	[82]
Pure water	997.1	4179	0.613	[43, 77]
Ethylene glycol	1113.2	2470.2	0.258	[43, 84]
Engine oil	870	2012	0.142	[85]

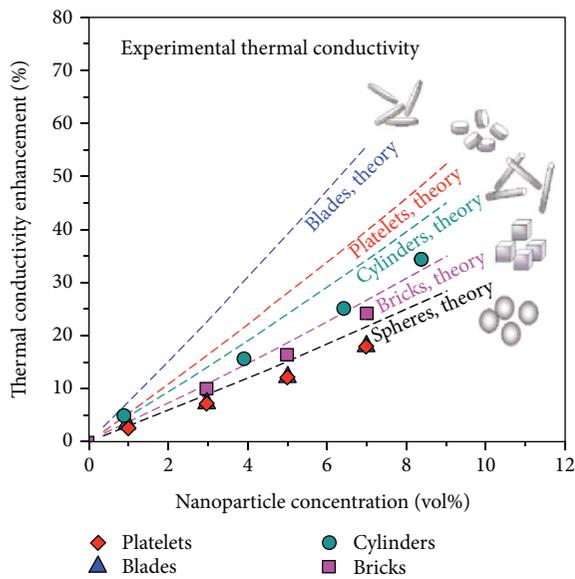


FIGURE 7: Effect of nanoparticle shape on the thermal conductivity of alumina nanofluid at different values of volume of fractions [87].

However, using a specific type of surfactant depends on the type of both the nanoparticle and base fluid [90].

7. Conclusion

This article provides a review of the most recent nanotechnology applications in photovoltaic thermal solar systems. We study the different types of nanoparticles and nanofluids that have been utilised previously in the literature and shortlist the methods used for their preparation. Both PV/T and CPV/T systems have been studied, and the relevant outputs have been collated together to summarize the potential benefits of using nanofluids. Further, we highlight the important parameters that can improve the performance of the nanofluids.

8. Future Perspectives

It is clear that the application of nanofluid in the solar energy field has a promising future. Therefore, more experimental work needs to be conducted especially with CPVT systems. Large scale studies for solar thermal systems would be important in order to verify the extent that nanofluids can enhance performance. This research should be conducted along with a cost analysis of the system. In addition, more experimental and simulation work should be carried out by using

carbon-based nanoparticles to take advantage of their higher thermal conductivity.

Data Availability

In support of open access research, all underlying article materials (data, models) can be accessed upon request via email to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

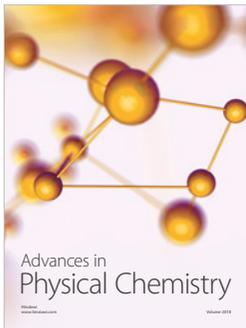
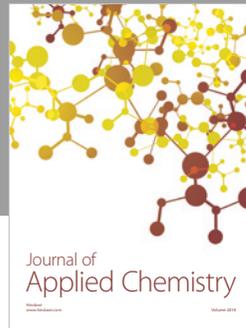
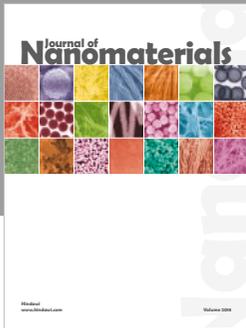
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